Electrostatic Switched Radiator For Space Based Thermal Control

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Abstract. . This paper describes a new thermal control device, termed an electrostatically controlled radiator (ESR) which uses electrostatic hold-down of a high emissivity composite film to control spacecraft skin temperature. The electrostatic hold-down switches the mode of heat transfer from the spacecraft skin from conduction to radiation. The effect is a large change in apparent emissivity. This device can operate effectively with moderate levels of DC voltages (i.e. 200 – 500V). Application of the voltage results in the high emissivity state while removal gives the low ε state. It should be noted that the ESR device basically operates as a high quality capacitor (C ~ 400 nF/m^2). Thus, if the control voltage is simply removed (as opposed to shorted) from the ESR film, the high emissivity state has a limited memory. In this paper, we provide experimental results of large effective emissivity changes having been achieved. Individual ESR devices have been fabricated with measured emissivity changes of approximately .74. Additionally, some ESR devices have been fabricated which achieved a maximum measured ε of .9; other samples have been produced which achieved a minimum ε of .1. Thus, with further material research and development and production process controls, it is expected that devices which can achieve a Δε of .8 can be produced.

THEORY OF OPERATION

The approach is based on the use of a cover film that is attracted to the skin of the spacecraft electrostatically. When attracted, it makes a good thermally conductive contact so the emitting surface of the cover is at the skin temperature. The outer surface of this cover is fabricated with a high emissivity, so the skin has a high effective emissivity (~1). In the released state, the thermal contact is now only by radiation so the only energy that the outer cover can radiate (at equilibrium) is that radiated from the skin, which is fabricated with a low emissivity. The emissivity of the outer skin doesn't change, however its temperature drops and the result is a drop in the radiated energy. This approach avoids the need for an IR transparent conductor, which is always difficult since transparent conductors (wide band gap semiconductors with a high electron concentration), have significant absorption in the IR. In addition, this approach has very limited material requirements on the front surface, so conventional white paints can be to used to control solar absorbance. This concept is shown in Figure 1 and analyzed below.

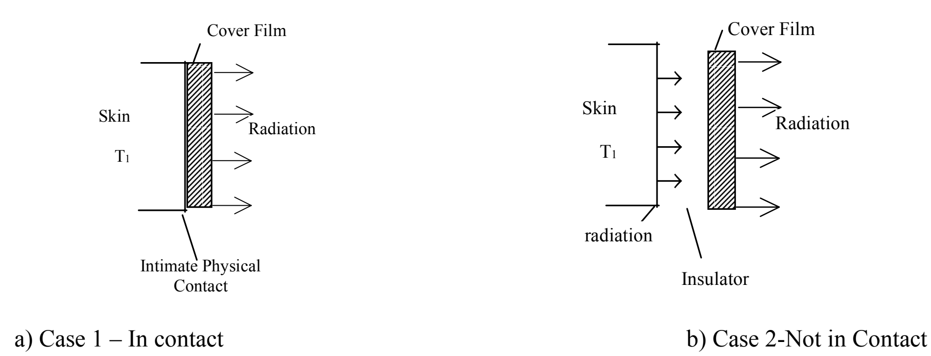

FIGURE 1. ESR Theory of Operation.

With good thermal contact (Figure 1a), the temperature of the cover film is at skin temperature T, then the energy radiated is given by (Liboff, 1992):

$$W(E)=\varepsilon_1 P(T) \tag{1}$$

where ε_1 is the emissivity of the outer surface and P(T) is the power radiated at a photon energy E at the surface temperature T (skin temperature)

$$P(E,T)=\frac{2\pi E^3}{c^2 h^3}\left(e^{E/kT}-1\right)^{-1} \tag{2}$$

Note that the key element is the intimate contact so that the temperature of the cover film is at the temperature of the skin.

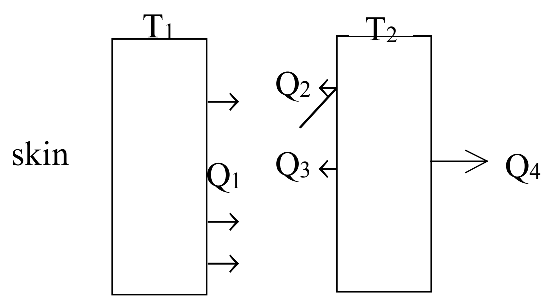

FIGURE 2. Heat Flow with Film Not In Contact.

Referring to Figure 2, when the film is not in contact, it can be modeled as follows. Q_1 is the energy radiated by surface 1 at skin temperature T_1 (fixed) with the surface emissivity ε_1. This heat is absorbed by surface 2, heating it to temperature T_2. The heat loss from surface 1 is the radiation from this body Q_1 minus the energy reabsorbed (which is a the reflected energy from surface 2) and the radiated energy from surface 2 (Holman, 1986);

$$Q_{loss1}=Q_1-(Q_2+Q_3) \tag{3}$$

where Q_2 is the energy reflected back from surface 2 and Q_3 is the radiated energy from surface 2 at unknown temperature T_2. With the assumption of infinite, parallel surfaces and ignoring multiple reflections:

$$Q_2 = Q_1 \cdot R_2 = Q_1\,(1-\varepsilon_2)\ \text{(with non transparent substrate - A=}\varepsilon\text{)} \tag{4}$$

This reduces to

$$Q_{netLoss1}=\varepsilon_1\varepsilon_2 P(T_1)-\varepsilon_2\, P(T_2) \tag{5}$$

The heat radiated from the surface to space is

$$Q_3 = \varepsilon_3\, P(T_2) \tag{6}$$

The steady state will occur when T_2 reaches a temperature such that $Q_{abs} = Q_{rad}$. Therefore we obtain

$$Q_{abs}=Q_1\cdot(1-R_2)=Q_1\varepsilon_2=\varepsilon_2 P(T_1) \tag{7}$$

and

$$Q_{rad}=\varepsilon_2 P(T_2)+\varepsilon_3 P(T_2) \tag{8}$$

Employing the equilibrium condition, we obtain

$$\varepsilon_2 P(T_1) = P(T_2)(\varepsilon_2 + \varepsilon_3) \tag{9}$$

Although we could solve for T_2 as function of ε_1, ε_2, ε_3 and T_1, we can see a maximum, for our applications, will occur with $\varepsilon_3 = 1$. This is the maximum heat radiated when the film is in contact with the skin. This also allows us to solve for T_2 as a function of ε_1 and ε_2. In this case, the total energy radiated by the system is that radiated from the outer skin, at unknown temperature T_2 or:

$$Q_T = \varepsilon_3 P(T_2); \tag{10}$$

which is equal to:

$$Q_{net\,1} = P_1(T_1) \cdot \varepsilon_1 - P_2(T_2)\,\varepsilon_2 \tag{11}$$

We ignore multiple reflection bouncing back and forth between 1 and 2 (this is a valid assumption since $\varepsilon_2 \cong 1$). Thus, we obtain

$$Q_3 = P(T_2) = \varepsilon_2 \varepsilon_1 P(T_1) - \varepsilon_2 P(T_2) \tag{12}$$

$$P(T_2) \cdot [1 + \varepsilon_2] = \varepsilon_2 \varepsilon_1 P(T_1) \tag{13}$$

or finally

$$P(T_2) = \frac{\varepsilon_2 \varepsilon_1}{1 + \varepsilon_2} \cdot P(T_1) \tag{14}$$

Since ε_2 is approximately equal to 1, we obtain

$$P(T_2) \cong \frac{\varepsilon_1}{2} \cdot P(T_1) \tag{15}$$

Thus the effective emissivity of the structure goes from ε_3 to $\varepsilon_1/2$. If $\varepsilon_1 \cong 0.1$, then the system switched from $\varepsilon \cong 1$ to $\varepsilon \cong 0.05$. Very high values and very low values for surface 1 and 3 respectively are easily achievable since these are conventional materials.

DEVICE CONSTRUCTION

A sketch of the ESR device is shown in Figure 3. It consists of a composite cover film anchored to the skin of the spacecraft at the edges. This cover film consists of a high dielectric constant insulator with good dielectric strength and coated with an electrically conductive layer. This outer surface of the cover film should have a very high emissivity, ideally with low visible absorptance. Since there are few other restrictions on this cover, this combination can be achieved with an appropriate paint or, for better performance, a multilayer thin film designed for very low visible absorbance. The top surface of the skin should have a very low emissivity, i.e. sputtered gold. A picture of an operational ESR is shown in Figure 4.

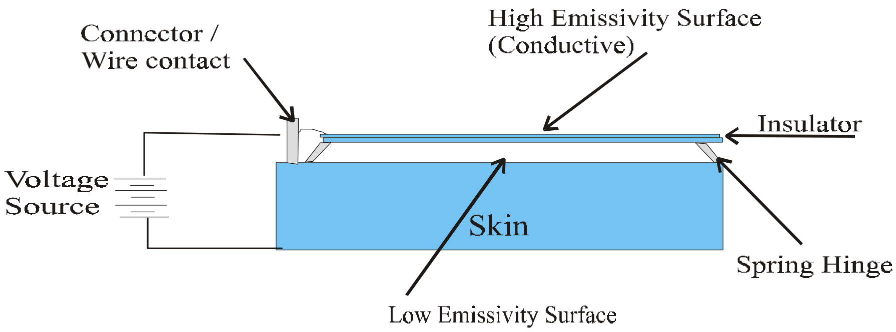

FIGURE 3. ESR Construction.

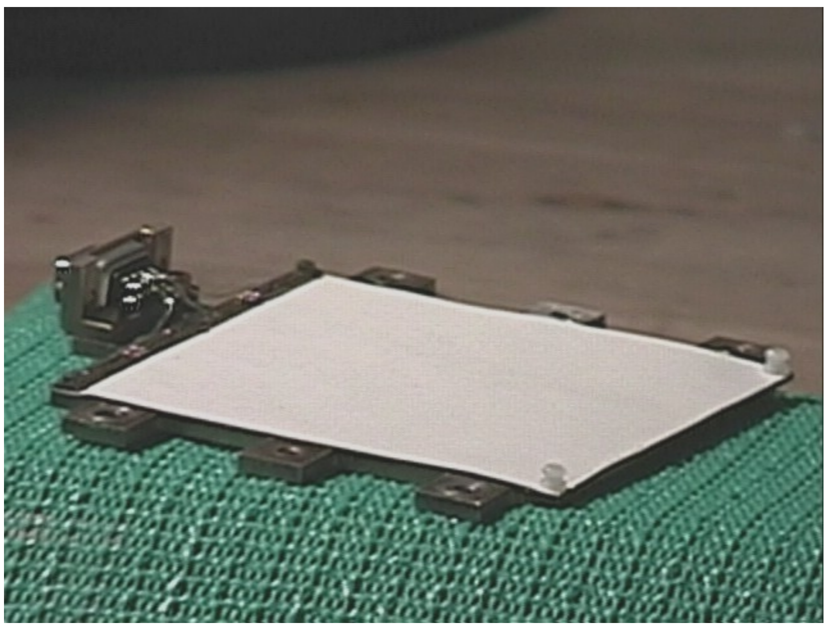

FIGURE 4. ESR Test Assembly Including Mounting Brackets and Electrical Connectors.

TESTING AND EXPERIMENTAL RESULTS

Since this device requires space-like conditions to operate; it was necessary to construct a system which would simulate these conditions for testing. A sketch of this system is shown in Figure 5. The sample is placed on a thermal control plate and the heat loss is measured either by measuring the temperature change with time, or the power required to maintain temperature and is basically a calorimetric approach. Although the heat loss with switching can give an accurate measure of a change of emissivity, stray losses (radiation from the back, un-switched areas, stray wires, leads, etc.), requires a calibrated sample to obtain emissivity values. Our calibration used a sputtered gold film as the “zero” and a black paint for the high value ($\varepsilon \sim .9$).

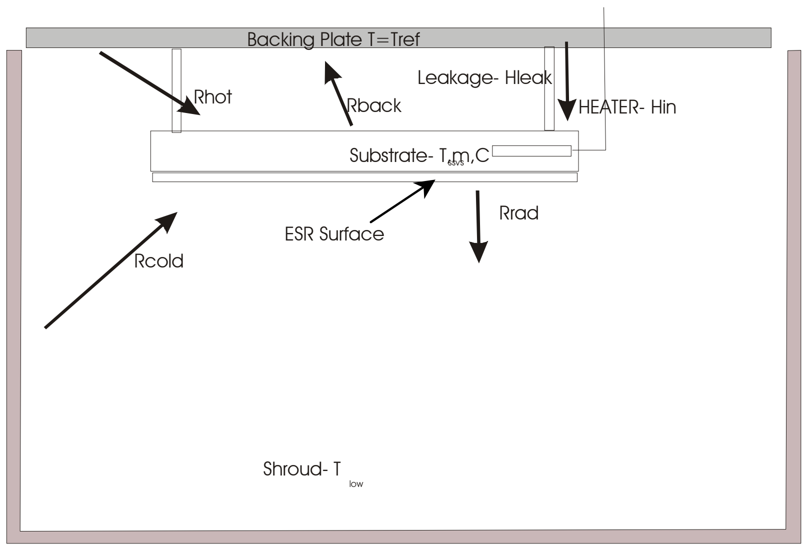

FIGURE 5. Sketch of Emissivity Measurement System.

Figure 6 shows measured results for a sample consisting of a cover film with a thin aluminum film. For this measurement, the voltage was applied while the sample was warm and showed basically the best performance that can be obtained, with a Δε of .74. Unfortunately, when this sample was left in the "off" state, the film took a "set" and the "on" values decreased drastically. This problem likely can be resolved by careful design both of the "hinge" and the material selection.

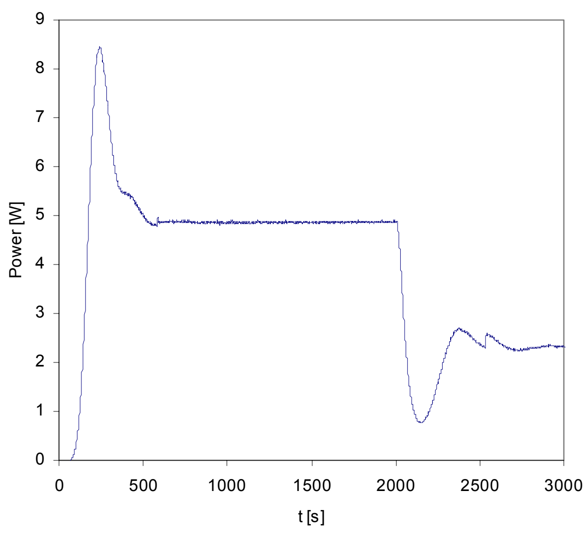

FIGURE 6. Power Input Measurements of Thin Metallized ESR. Δε =.74.

Figure 7 shows the results obtained on a more reproducible and controllable device, with some sacrifice in emissivity. The film surface area was 9.2 cm x 9 cm and the radiation switched was 21.87 mW/cm^2. This corresponds to a Δε of 0.512 (high ε of .9 and a low ε of .388). This particular sample was manufactured with a more thermally conductive top electrode. This configuration likely increased the lateral heat flow in the "off" state and limited the low temperature in this off-state. The more modest Δε which results also has a much lower temperature excursion. The calculated temperature for this cover film for a low ε of .388 is 269K. There is minimal stress on the cover film in this “off” state and careful design of the hinge mechanism should allow reliable operation at much lower temperatures with the resulting larger control range for the radiation from the surface.

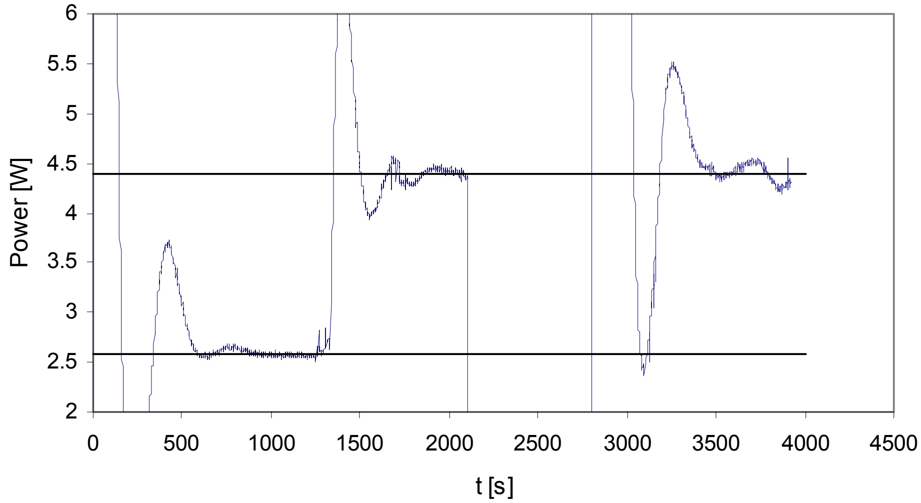

FIGURE 7. Power Input Measurements of Thick Metallized ESR. $\Delta\varepsilon = .51$.

CONTROL SYSTEM

The initial application is a demonstration on the ST-5 satellite. For this application, the ESR will be mounted on an aluminum substrate. This simulates the spacecraft and serves as a heat reservoir from which energy is stored (ESR off) or radiated to space (ESR on). The entire system can be modeled via an electrical analog with the mounting washers and other connections (such as electrical control wiring) being represented by resistors, the Al base plate as a capacitor and the ESR as a constant current source. Since all of the thermal resistance in the system is in this resistance, it can be treated as a lumped equivalent resistance. The total resistance is dominated by the resistance due to the mounting washers, and since for parallel resistances $R < R_{i,max}$ this will provide a useful limiting case. For purposes of the model, the value 0.1 W/K for the conductance between the spacecraft deck and ESR was used (this value was taken from the maximum permitted per the ST-5 Performance Specification documentation, for which the ESR will be flight tested).

The ESR can be modeled as a constant current source for both the on and off states. With these assumptions, the system behaves according to the following ordinary differential equation (Holman,1986, Öziçik,1980)

$$\frac{dT_e}{dt} = \frac{1}{C_v}\left[\frac{1}{R}(T_s - T_e) - Q_e\right] \tag{16}$$

where T_e is the ESR temperature, T_s is the spacecraft skin temperature, Q_s is the heat transferred via radiation by the ESR, R is the thermal resistance (due to the mounting washers, connecting wires, etc.) and C_v is the heat capacity of the ESR device (i.e. aluminum base plate, mounting hardware, wiring and connectors).

The model used the values T_s = 293K, T_e (t=0) = 298K and R = 10 K/W. Additionally, the model used C_v = 35.8 J/K for the device specific heat. This value was calculated from values of the mass of the constituent parts of the ESR and tabulated values of the constituent material specific heat. The energy radiated by the ESR is obtained by a combination of the effective active area of the ESR film and the area of other constituent parts (hold-down screws, etc.) and is given by

$$Q_e = (A_e\varepsilon_e + A_o\varepsilon_o)Q_{max} \tag{17}$$

where $A_{e,o}$ is the effective fractional area of the ESR film and other device components respectively (A_e set to .85 and $A_o = 1 - A_e$). ε_e is the ESR film emissivity and ε_o is the emissivity of the other device materials (ε_o set at .5). Q_{max} is the maximum theoretical radiated heat transfer from the ESR temperature to a cold space background (Q_{max} = 45.9 mW/cm^2). Using these values, a family of curves for the time evolution of the ESR temperature for different values of ESR film emissivity was obtained. These results are shown in Figure 8.

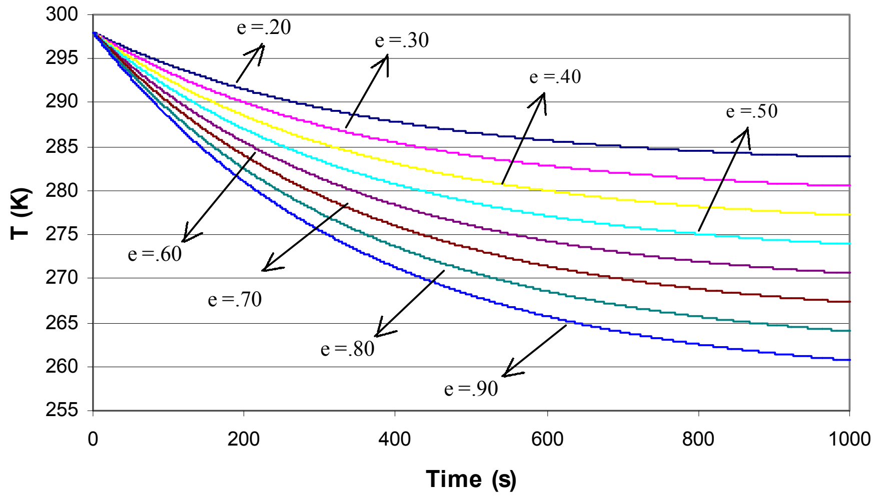

FIGURE 8. ESR Substrate Temperature for Different ESR Film Emissivity Values.

These results can be used to determine the effective control range of the ESR for the ST-5 spacecraft application. As an example, given an on-state ESR film emissivity of .9 and an off-state value of .5, the ESR will be capable of controlling temperature between approximately 260 and 272K.

The ESR is an off/on device. To vary the emissivity, it is possible to switch the entire area off/on to give a time average emissivity, or break up the surface and switch different areas. Switching different areas appears slightly easier to implement than time control switching of the entire area. A schematic of the ESR control system is shown in Figure 9 with a single inverter switched to different areas. The circuitry consists of an Emco Q05-5 inverter, which outputs 0 to 500 volts with a 5-volt input. A high value resistor (>10MΩ) is used for each segment. This limits the current flow when the samples are switched on and also allows a single transistor to control the segment voltage.

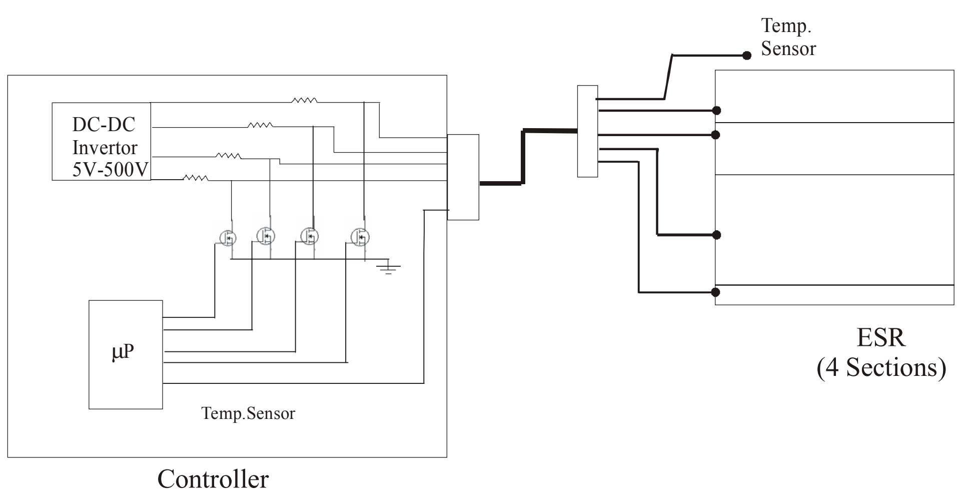

Figure 9. Control Electronics. Inverter Output is Switched to Different ESR Areas.

CONCLUSIONS

In this paper we have described a new thermal control device which uses electrostatic hold-down of a high emissivity composite film to control spacecraft skin temperature. We also provided experimental results which indicate large effective emissivity changes have been achieved. Individual ESR devices have been fabricated with measured emissivity changes of approximately .74. Additionally, some ESR devices have been fabricated which achieved a measured ε of .9; other samples have been produced which achieved a minimum ε of .1. Thus, with further material research and development and production process controls, it is expected that devices which can achieve a $\Delta\varepsilon$ of .8 can be produced. Finally, a proposed control scheme for space based application of ESR's as a spacecraft temperature control device was briefly described.

NOMENCLATURE

c = speed of light in vacuum ($2.998\text{x}10^{8}$ m/s)
h = Planck's constant ($6.626\text{x}10^{-34}$ Js)
k = Boltzmann's constant ($1.381\text{x}10^{-23}$ J/K)
A = effective fractional area
C = capacitance per unit area (F/m^2)
C_v = heat capacity (J/K)
E = Photon energy (J)
P = Power radiated at photon energy E and surface temperature T
R = Thermal resistance (Ks/J)
T = Temperature (K)
Q = Radiative heat transfer rate (J/s)
W = Energy transfer rate (J/s)
ε = emissivity
$\Delta\varepsilon$ = change in emissivity between operational states

ACKNOWLEDGMENTS

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